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Palaeoenvironmental change in the Gulf of Carpentaria (Australia) since the last interglacial based on Ostracoda

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Abstract

Throughout the last glacial cycle, the region between Australia and New Guinea, which is today known as the Gulf of Carpentaria, has oscillated from open shallow marine conditions to a large, land-locked freshwater lake, including periods of subaerial exposure. Ostracod faunal assemblages and variations in the valve morphology, preserved in the sediments of the gulf, record these changes. A 14.8 m long core (MD972132) extracted from near the centre of the modern Gulf of Carpentaria, spanning the last 130 ka BP provides the basis of this study.

Environmental facies were determined by R- and Q-mode cluster analysis of the ostracod assemblage data, including 72 species, and comparison with modern analogues from both the Gulf of Carpentaria and Southeast Asian region. Using these methods, six clearly distinct biofacies were identified:

- (i) open shallow marine facies, including bairdiids, pectocytherinids and cytherettids;
- (ii) shallow marine facies, dominated by *Cytherella* and *Hemikrithes*;
- (iii) marginal marine facies, including *Xestoleberis* and *Praemunita*;
- (iv) tidal channel facies, dominated by *Loxococoncha*;
- (v) estuarine assemblage, comprising *Venericythere* and *Leptocythere*;
- (vi) non-marine facies
 - a. brackish lagoon/lake facies dominated by *Cyprideis* and *Leptocythere*;
 - b. freshwater facies, including *Ilyocypris*, with *Cyprinotus* and *Cypretta*.

In addition, morphological variation of valves of the more “plastic” species, in particular *Cyprideis australiensis* and *Leptocythere hartmanni*, was observed and related to environmental variables, including salinity and solute composition. These two species occur through more than half of the length of the core and show significant variability. *C. australiensis* with irregular-shaped sieve pores is associated with heavily reticulated valves of *L. hartmanni*, around 90–70 ka BP, indicating increased salinity and carbonate-limited environments. Conversely, *C. australiensis* with round sieve pores occurs with finely reticulated valves of *L. hartmanni* from around 50 ka BP, in fresher, carbonate-rich environments. The preservation of valves was also noted so as to infer post-depositional effects, revealing shoreline features, channel activity and subaerial exposure.

Combined ostracod biofacies and morphological analysis reveals a fluctuating marine environment through Marine Isotope Stage (MIS) 5, terminating in a restricted lagoon around 90 ka BP, followed by an extensive period of subaerial exposure in this

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region of the gulf. MIS 3 marks a return of marine conditions and an increase in fluvial activity. Lake Carpentaria then appears as a permanent feature, at least to the current 60 m depth contour, from around 40 ka BP, with the freshest water occurring around 16 cal. ka BP, prior to the most recent marine transgression, at 10.8 cal. ka BP. Although the presence of Lake Carpentaria had previously been identified, this study extends the knowledge of the region through the last glacial cycle and provides greater detail of the sequential biofacies.

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1. Introduction

1.1. The Gulf of Carpentaria

The Gulf of Carpentaria is an epicontinental sea located between Australia and New Guinea (Fig. 1). The gulf is bordered to the north by the south coast of West Papua (Indonesia) and Papua New Guinea and to the south by the north coast of Australia from Arnhem Land, Northern Territory in the west to Cape York Peninsula, Queensland in the east. This broad, shallow embayment reaches a maximum water depth of 70 m near the eastern margin. Below 50 m water depth, the sea floor is essentially flat with a gradient of about 1:13,000 (Edgar et al., 2003).

The Arafura Sill is a sedimentary feature that separates the gulf from the Indian Ocean to the west, 53 m below present sea level (bpsl). Seismic profiles taken across the sill reveal numerous previously incised channels. The most recent of these are cut to depths of 62 m and 75 m (Jones and Torgersen, 1988).

Torres Strait is a shallow platform extending from Papua New Guinea to the tip of Cape York Peninsula and separating the Gulf of Carpentaria from the Pacific Ocean. The Strait is generally between 15 m and 60 m deep and is bounded on the eastern side by a sill only 12 m deep.

Throughout the Quaternary, during times of low sea level, the gulf was isolated from either the Pacific Ocean alone, forming an embayment, or the Indian Ocean as well. At these times, a large, shallow lake, known as Lake Carpentaria, existed in the basin. The presence of Lake Carpentaria has been identified from previous studies (Nix and Kalma, 1972; Smart, 1977). Episodes of basin-wide subaerial exposure have also been noted (Chivas et al., 2001).

During the 1980s the sedimentological units (Table 1) and hydrological history of the gulf region over the last 40 ka were established (Torgersen et al., 1983, 1985, 1988; Jones and Torgersen, 1988). These studies included identification of major ostracod groups and chemical analysis (Mg/Ca, Sr/Ca and $^{87}\text{Sr}/^{86}\text{Sr}$) of ostracod

valves for facies determination and climatological information (De Deckker et al., 1988; McCulloch et al., 1989).

1.2. Ostracod ecology

Ostracods are small bivalved crustaceans, present in both marine and non-marine environments, ranging from the deep ocean to freshwater lakes and including temporary pools, springs, groundwater, rivers, estuaries, swamps and even some semi-terrestrial habitats. They provide an eminently suitable proxy for the study of past environments as they are generally abundant and well preserved in the fossil record and are sensitive to a broad range of ecological variables, with most taxa living along environmental gradients. Palaeoenvironmental reconstruction may be ascertained by: a) extrapolating modern ecological constraints to fossil assemblages and b) morphological analysis of the carapaces with respect to physical and chemical parameters both during the organisms' life time and post-deposition.

For recent reviews of ostracod ecology and their use in palaeoenvironmental studies, the reader may refer to the volumes by Holmes and Chivas (2002) and Park and Smith (2003).

1.3. Morphological variation

Morphological features of some ostracod species, such as surface reticulation, carapace size and thickness and sieve pore shape, may vary extensively in response to fluctuating environmental conditions (Fig. 2). Numerous studies of taxa in waters transitional between fresh and saline have revealed an intraspecific gradational change in ornamentation (Hartmann, 1982; Carbonel, 1988; Carbonel and Hoibian, 1988; Peypouquet et al., 1988). The variation refers to the degree of ornamentation, the locus of which is genetically predetermined (Carbonel, 1988). This, in turn, corresponds to the carbonate equilibrium at the sediment–water interface, controlled by the biological consumption/modification of organic matter; a relationship termed the

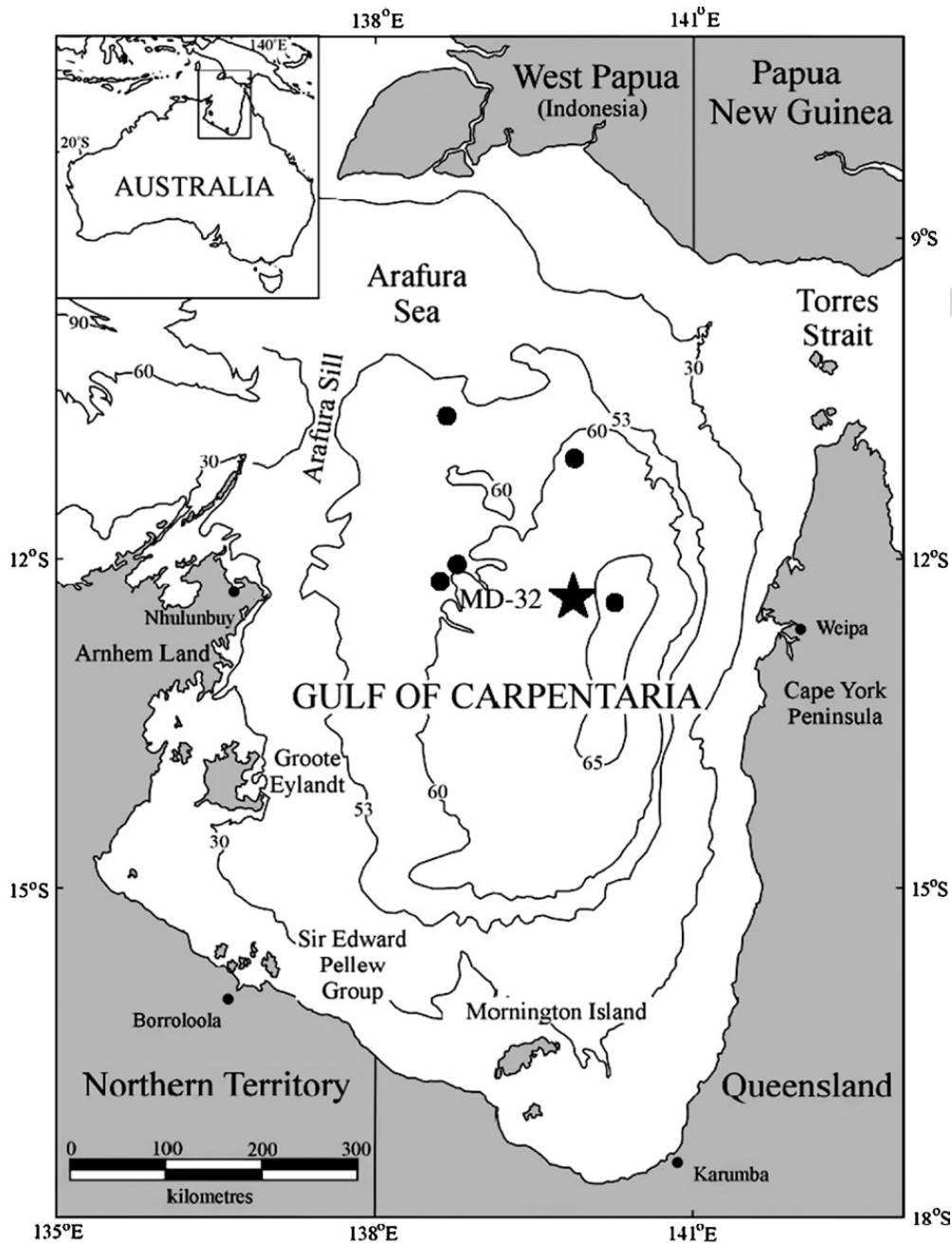


Fig. 1. Map showing the location of core MD-32, presented in this study (represented by a star). The bathymetric contours are in metres. Circles denote the other cores collected for this project.

aggradation–degradation “theory” of [Peypouquet et al. \(1980\)](#). This phenomenon has been observed in the present study for the taxa *Leptocythere hartmanni* and *Leptocythere lacustris*, which are here considered to be conspecific. These were previously described as two separate species; the former, originally as *Callistocythere hartmanni* by [McKenzie \(1967\)](#), changed to *Leptocythere* by [Hartmann \(1979\)](#), and the latter as *L. lacustris* by [De Deckker \(1981a\)](#). The present study reveals a clear gradation between the two morphotypes, henceforth referred to as *L. hartmanni* R for the finely

reticulate morph and *L. hartmanni* B for the bulbous morph (Fig. 2A; [Reeves, 2004](#)).

Sieve pores, which occur only in cytheroidean podocopans, show a variety of shapes (Fig. 2B). These have been attributed to variations in the salinity of the host waters ([Rosenfeld and Vesper, 1977](#)) although this is based on observation, rather than empirical testing or culturing experiments. The Northern Hemisphere ostracod, *Cyprideis torosa*, has been the main focus of study, however the phenomenon is known for other taxa. Of the three sieve pore types identified, [Rosenfeld and Vesper](#)

Table 1
Sedimentary units for the Gulf/Lake Carpentaria, 40 ka BP to present, defined by Torgersen et al., 1985, 1988; De Deckker et al., 1988

Unit	Sediment	Ostracods	Age (ka BP)	Interpretation
I	Green–grey shelly ooze	<i>Polycope</i> , <i>Bairdia</i> *, (<i>Cyprideis</i>)	0–10	Shallow marine, relict surface
II	Dark grey fine mud	<i>Ilyocypris</i> , <i>Cyprideis</i>	10–26	Fresh-brackish lake
III	Authigenic calcite laminae	Bleached <i>Cyprideis</i>	~ 26	Stratified shallow waterbody
IV	Shell-hash layer	<i>Cyprideis</i>	26–36	Brackish, productive lake
V	Mottled dark-grey fine mud	<i>Cyprideis</i> , <i>Uroleberis</i> *, <i>Monoceratina</i> *	<36	Brackish lake, pedogenesis

*The identification of these taxa have been modified in this study. The equivalent taxa are: *Bairdia*=*Paranesidea*, *Uroleberis*=*Venericythere*, *Monoceratina*=*Neomonoceratina*.

(1977) found round forms dominant in freshwater and irregular shapes dominant in hypersalines conditions. The elongate form appears to be intermediary to these two end-members. Rather than salinity *per se*, De Deckker (2002) relates the variation in pore shape to a reflection of the ‘readiness’ with which the ostracod secretes its carapace; with more irregular forms of sieve

pore shape indicative of more stressed conditions such as poor calcite saturation in highly saline estuarine waters. Observations of sieve pores of *Cyprideis australiensis* have been made in core MD-32, used in this study.

Noding, which is a common phenomenon of *Cyprideis torosa* in low salinity waterbodies in the Northern Hemisphere (Keyser, 2005), has not been observed in *Cyprideis australiensis*. Indeed, no noded forms have been identified in Australia, including this study.

1.4. Preservation

Palaeoecological information can be extracted from ostracod valves and assemblages regarding both ambient conditions at the time of valve formation and post-depositional effects. The ratio of adult to juvenile valves, or population age structure, provides information on the energy of the environment, current effects and dissolution (e.g. Brouwers, 1988; Boomer et al., 2003; Ruiz et al., 2003). In addition, the absence of adult valves may represent a change in conditions during the life cycle of the ostracod, such as a decrease in temperature or dissolved oxygen concentration (De Deckker, 1988, 2002). As such, population age structure may be indicative of palaeoenvironments (e.g. Whatley, 1988; Boomer et al., 2003).

The preservation of the valves may give some clues to the post-depositional conditions of the environment

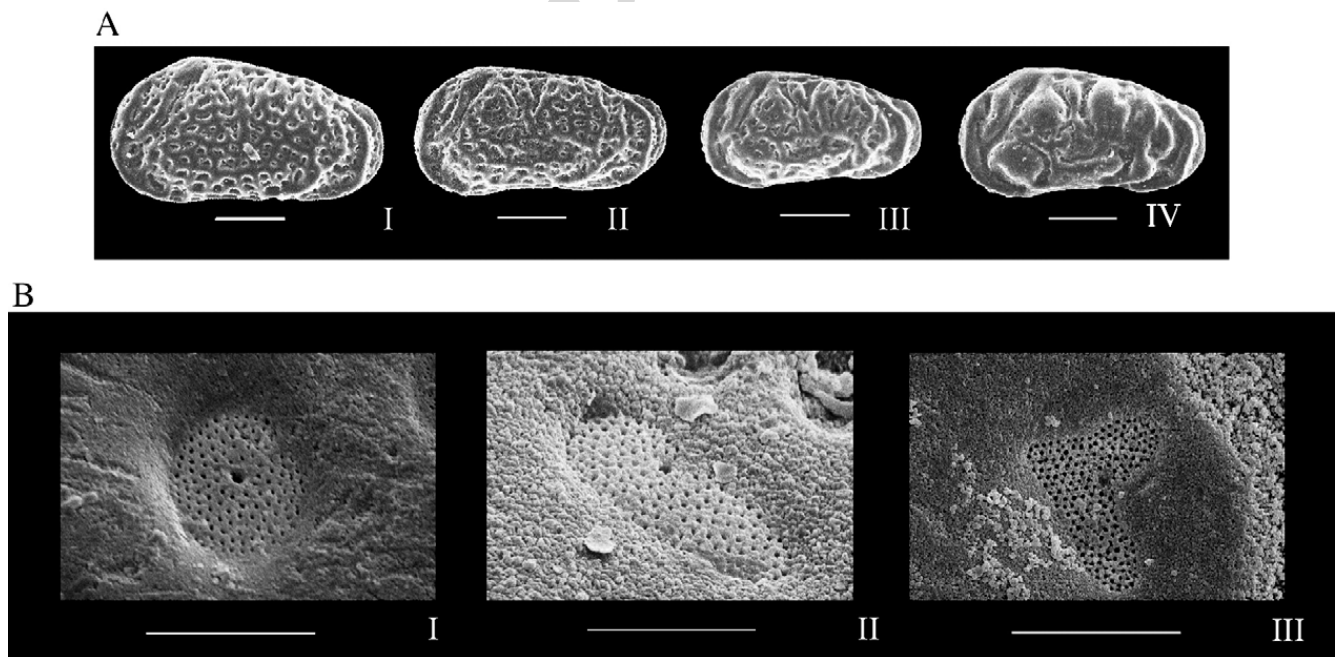


Fig. 2. (A) Morphological variation of *Leptocythere hartmanni*, taken from core MD-32. I. Finely reticulate (*L. hartmanni* R) (MD32-150 — where 32 represents the core number and 150 refers to the sample depth in centimetres), II. Reticulate (MD32-180), III. Coarsely reticulate (MD32-430), IV. Bulbous (*L. hartmanni* B) (MD32-560). The scale bar is 100 µm (B) Examples of sieve pore morphology of *Cyprideis australiensis* from core MD-32. I. Round (MD32-500), II. Elongate (MD32-540), III. Irregular (MD32-490). The scale bar is 10 µm.

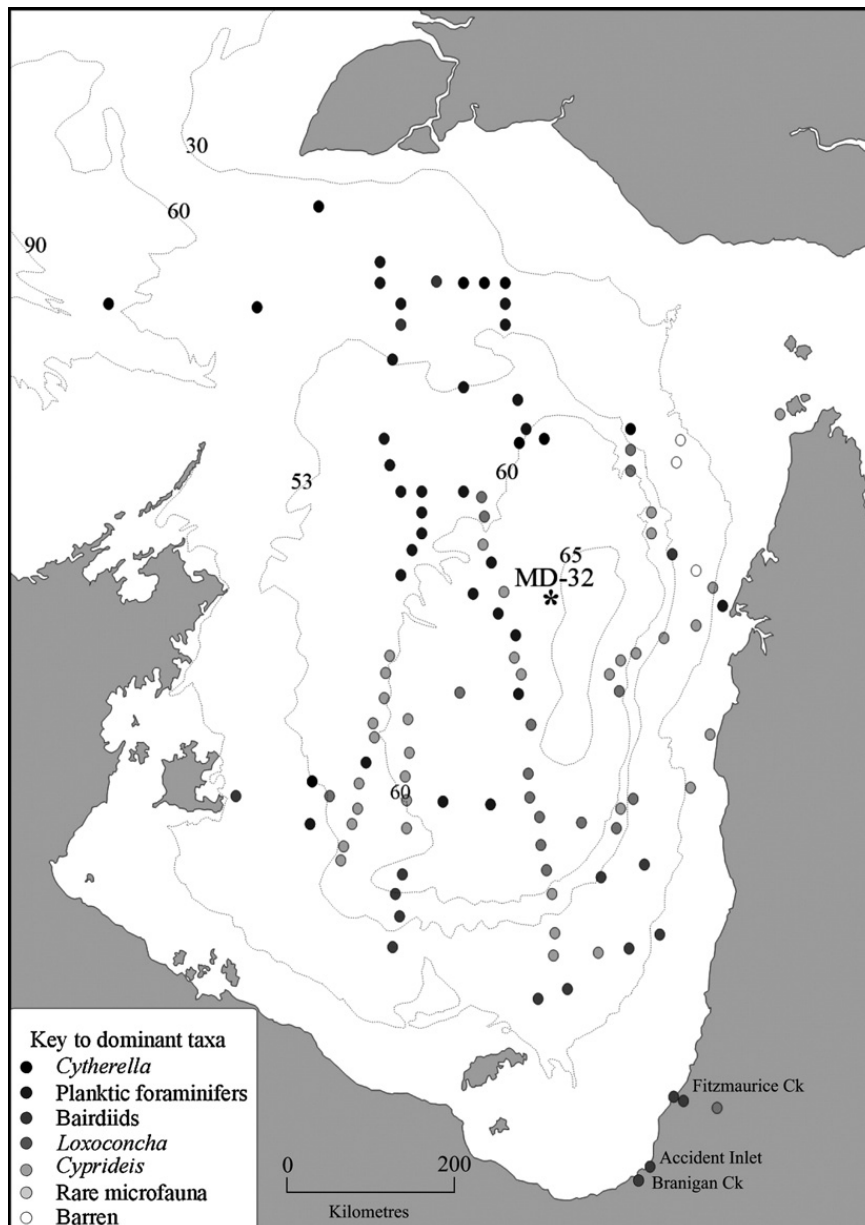


Fig. 3. Map showing the reconnaissance study localities and the distribution of dominant taxa present in the surface sediment samples of the Gulf of Carpentaria. The core locality of MD-32 is marked with an asterisk.

(e.g. De Deckker, 2002). Dissolution of ostracod valves is a common effect in eutrophic environments. The first sites of dissolution within the carapace are the sieve pores, as the shell is thinner at these points.

If bacterial activity is prominent in an anoxic environment, microscopic pyrite crystals form, adhering to the calcite valves and in some cases, particularly for interstitial ostracods, infilling the carapace (Oertli, 1971). The formation of pyrite must occur after the death of the ostracods, as very few species are able to tolerate anoxic conditions. If this pyrite is later exposed and oxidised, further dissolution of the valve may follow. De Deckker (1988) clearly illustrated the various

steps in the dissolution of *Cyprideis australiensis* fossil specimens from the Gulf of Carpentaria. Of interest is that dissolution of *C. australiensis* valves is initiated where the shell is thinnest, such as around the sieve pores. Minor dissolution, by way of modification of the carapace reticulation, may also be noted. This is due to fluctuations of the host water carbonate saturation at or near the sediment–water interface (Swanson, 1995).

Diagenesis of ostracod valves may take place within the sediment. Such effects should be observable on the ostracod valves, as a grainy or chalky texture when viewed under a microscope. Recrystallisation of ostracod valves, leading to a “sugary” appearance, is also possible in

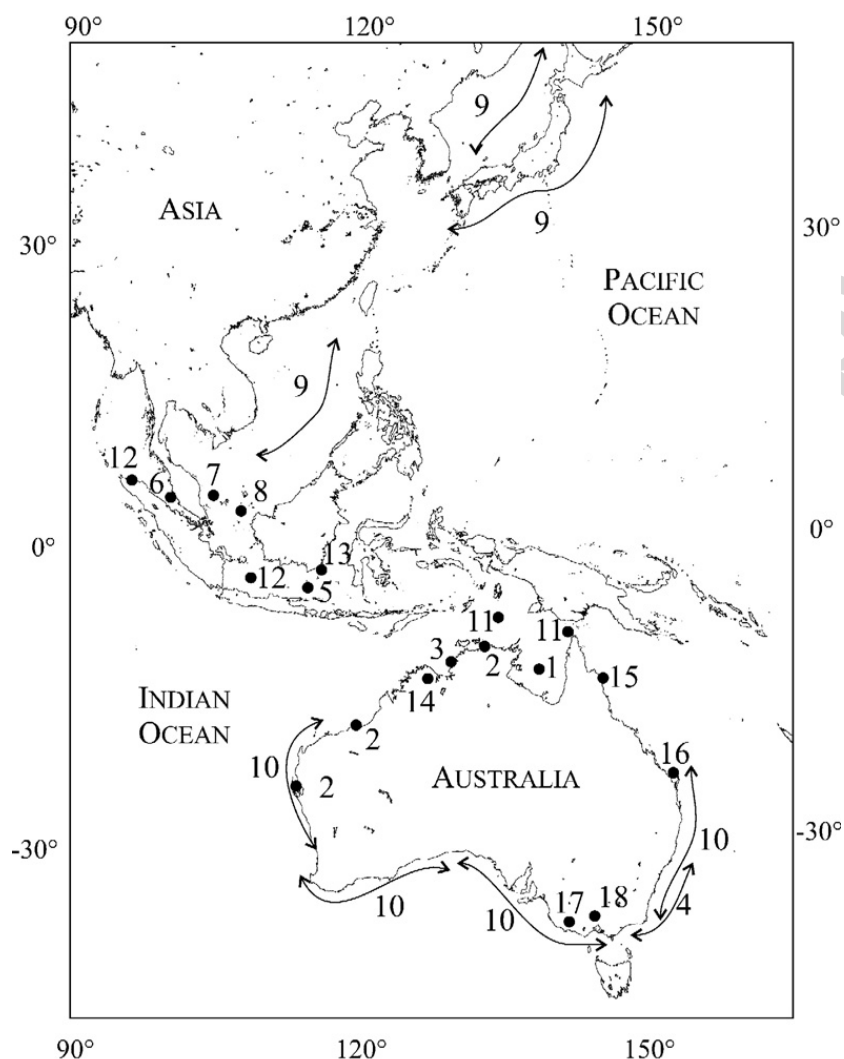


Fig. 4. Map showing the location of previous ostracod investigations referred to in this paper. The numbers refer to localities given in Table 2, with the addition of: 15. Labutis, 1977. 16. Behrens, 1991. 17. De Deckker, 1981b. 18. De Deckker, 1981c.

sediment influenced by a secondary water source that may be enriched with calcium carbonate. Alternatively, a calcareous coating may be formed around the entire carapace or encasing the individual valves (De Deckker, 2002).

2. Materials and methods

The Gulf of Carpentaria has formed the focus of a large multidisciplinary project to elucidate sea level, climatic, and hydrological change in tropical Australia (Chivas et al., 2001; Reeves et al., accepted for publication). To this end, six sediment cores, from 4.2 m to 14.8 m in length, were collected from water depths of 59 m to 68 m, ranging from the near bathymetric centre of the gulf to shallower areas to the northwest (Fig. 1). The longest of these cores, MD972132 (hereafter MD-32) (12°18.79'S, 139°58.73'E), taken from a modern water depth of 64 m bpsl, forms the basis of this study.

The methodology of core subdivision has been detailed previously (Chivas et al., 2001). Microscopic investigation of the >63- μ m fraction was performed systematically at 10-cm intervals, representing a total of 149 samples. The micropalaeontological subsamples, weighing approximately 8 g when wet, were oven dried at 40–60 °C overnight in 250-ml glass jars. After drying and reweighing, the jar was filled with de-ionised water and the sediment left to disaggregate for at least 15 h. The slurry was wet-sieved with de-ionised water through a 63- μ m-nylon mesh. The coarse fraction was oven-dried at 40–50 °C, weighed and stored. For samples weighing greater than 25 mg, aliquots of material were prepared for analysis using a microsplitter and reweighed.

Length and height measurements of ostracod valves were made to determine the ratio of adult to juvenile valves. In addition, a selection of adult *C. australiensis* valves, typically three from each sample where present,

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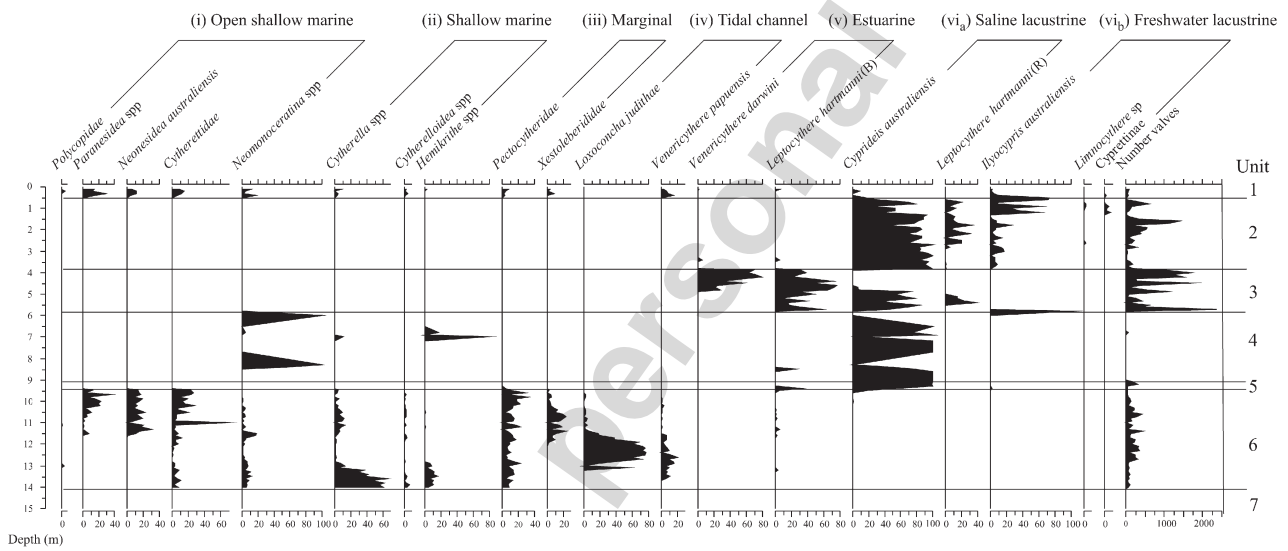


Fig. 5. Proportional distribution of key ostracod taxa (in %) as a function of depth in core MD-32. The absolute abundance of all ostracods (valves per gram of dry sediment) is shown in the right-hand column. Biofacies units (i–vi), represented by the horizontal divisions, are based on R-mode cluster analysis (Section 3.2). The sedimentary units (1 to 7) are the sequential vertical divisions (after Reeves et al., accepted for publication).

Table 2 (continued)

Species	1	2	3	4	5	6	7	8	9	10	11	12	13	14
<i>Keijia australis</i>	X	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Neomonoceratina bataviana</i>	X	X	X	–	X	X	X	X	X	–	X	X	X	–
<i>Neomonoceratina porocostata</i>	X	X	X	–	–	–	–	–	–	–	–	–	–	–
<i>paijenborchelle solitaria</i>	X	–	–	–	–	–	–	–	X	–	–	–	–	–
<i>Xestoleberis darwinesis</i>	–	X	–	–	–	–	–	–	–	–	–	–	–	–
<i>Foveoleberis cypraeoides</i>	X	–	X	–	X	X	X	X	X	–	X	X	X	–
<i>Limnocythere</i> sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	G
<i>Cyprideis australiensis</i>	X	–	–	X	–	–	–	–	–	X	–	–	–	–
<i>Hyocypris australiensis</i>	X	–	–	–	–	–	–	–	–	–	–	–	–	+
<i>Cyprinotus</i> cf. <i>cingalensis</i>	–	–	–	–	–	–	–	–	X	–	–	–	–	G
<i>Candonocypris</i> cf. <i>novaezelandiae</i>	–	–	–	–	–	–	–	–	–	–	–	–	–	G
<i>Cypretta</i> sp.	–	–	–	–	–	–	–	–	G	–	–	–	–	G
<i>Zonocypretta</i> sp.	–	–	–	–	–	–	–	–	–	–	–	–	–	–
<i>Darwinula</i> sp.	–	–	–	–	–	–	–	–	G	–	–	–	–	–

1. Yassini et al., 1993 (Gulf of Carpentaria)
2. Howe and McKenzie, 1989 (N.T. and W.A.)
3. Clarke et al., 2001 (Joseph Bonaparte Gulf)
4. Yassini and Jones, 1995 (SE Australia)
5. Dewi, 1997 (Java Sea-Bawean Is)
6. Whatley and Zhao, 1987, 1988 (Malacca Straits)
7. Zhao and Whatley, 1989 (Malay Peninsula)
8. Mostafawi, 1992 (Sunda Shelf)
9. Hanai et al., 1980 (Southeast Asia)
10. Hartmann, 1978, 1979, 1980, 1981, 1982 (W.S and E Australia)
11. Brady, 1866, 1880 (N. Australia, Indonesia)
12. Dewi, 2000 (Java Sea, S. Borneo)
13. Kingma, 1948 (Southeast Asia)
14. McKenzie, 1966 (NW Australia inland)

Legend: X=present, –=absent, G=genus.

were examined under Scanning Electron Microscope (SEM) for sieve pore morphology. Combinations of both male and female adult valves were studied, and all visible sieve pores analysed. The taxon *L. hartmanni* was given special attention, as the morphotypes show variation from finely reticulate valves (R) in fresh water, to heavily calcified valves (B) in saline water.

For the present study, a reconnaissance survey (Fig. 3) was made of surface grab samples previously collected from throughout the Gulf of Carpentaria (Phipps, 1966, 1970), the fauna of which has not previously been published. In addition, surface samples were examined from Accident Inlet and Branigan Creek, in the southeast of the gulf collected during a short field trip in 1999. Many of the species present in the core material were poorly represented or absent from these samples, hence much of the modern analogue data for the subfossil species have been obtained from the literature on modern ostracod taxonomy and assemblages from the Gulf of Carpentaria and surrounding regions (Fig. 4). Comparisons between these papers and material from the present study have been made to determine species identification, enable facies delineation and palaeoenvironmental re-

construction of the core assemblages, and establish affinities between the fauna of the Gulf of Carpentaria and other biogeographic zones.

3. Results

3.1. Ostracod analysis of core MD-32

Approximately 30,000 ostracod valves, representing 72 species of ostracods from 52 genera, were identified (Appendices 1, 2). Of these, 14 remain in open nomenclature, 8 having been figured before without full taxonomic description. A further 10 species are annotated 'cf.', indicating that the taxon is comparable with, but possibly not identical to a previously described species. SEM images of 70 taxa are presented in Plates 1–5 of Appendix 3.

The species abundance and diversity varies markedly throughout the core (Fig. 5), coinciding with distinct depositional environments. Six species are present in only one sample and 20 species are represented by no more than two valves per sample. Ostracods were not observed in 32 of the samples, however 48 samples

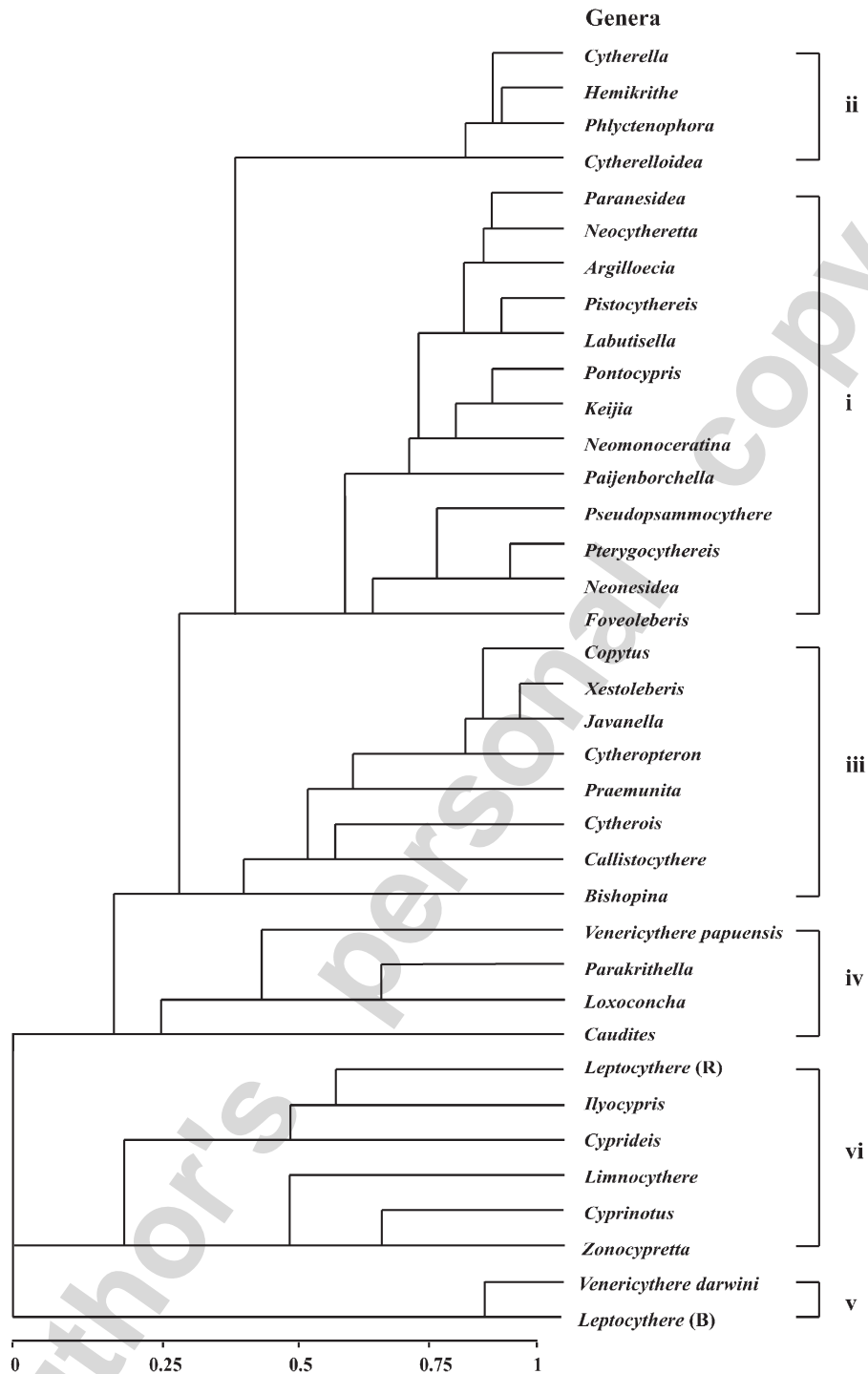


Fig. 6. R-mode cluster analysis of ostracods from core MD-32. The numbers (i) to (vi) are ordered in relation to the depth which is represented by the biofacies, from open shallow marine (i) to lacustrine (vi). This is the same numbering system applied to Fig. 5. The x-axis indicates the degree of correlation between the branches of the cluster.

contain greater than 10 species and 9 samples contain in excess of 100 valves per gram of dry sediment, dominated by just one or two species.

Many of the species identified are found in the modern Gulf of Carpentaria and surrounding estuaries. Yassini et al. (1993) record 44 species in common with

those of the core samples. The ostracod fauna display tropical–subtropical affinities. Taxa common to core MD-32 that have been described from regional studies are outlined in Table 2. Of the 72 species identified, 38% are common to the Arafura Sea and northern Australian waters (Brady, 1880; Hartmann, 1978; Howe and

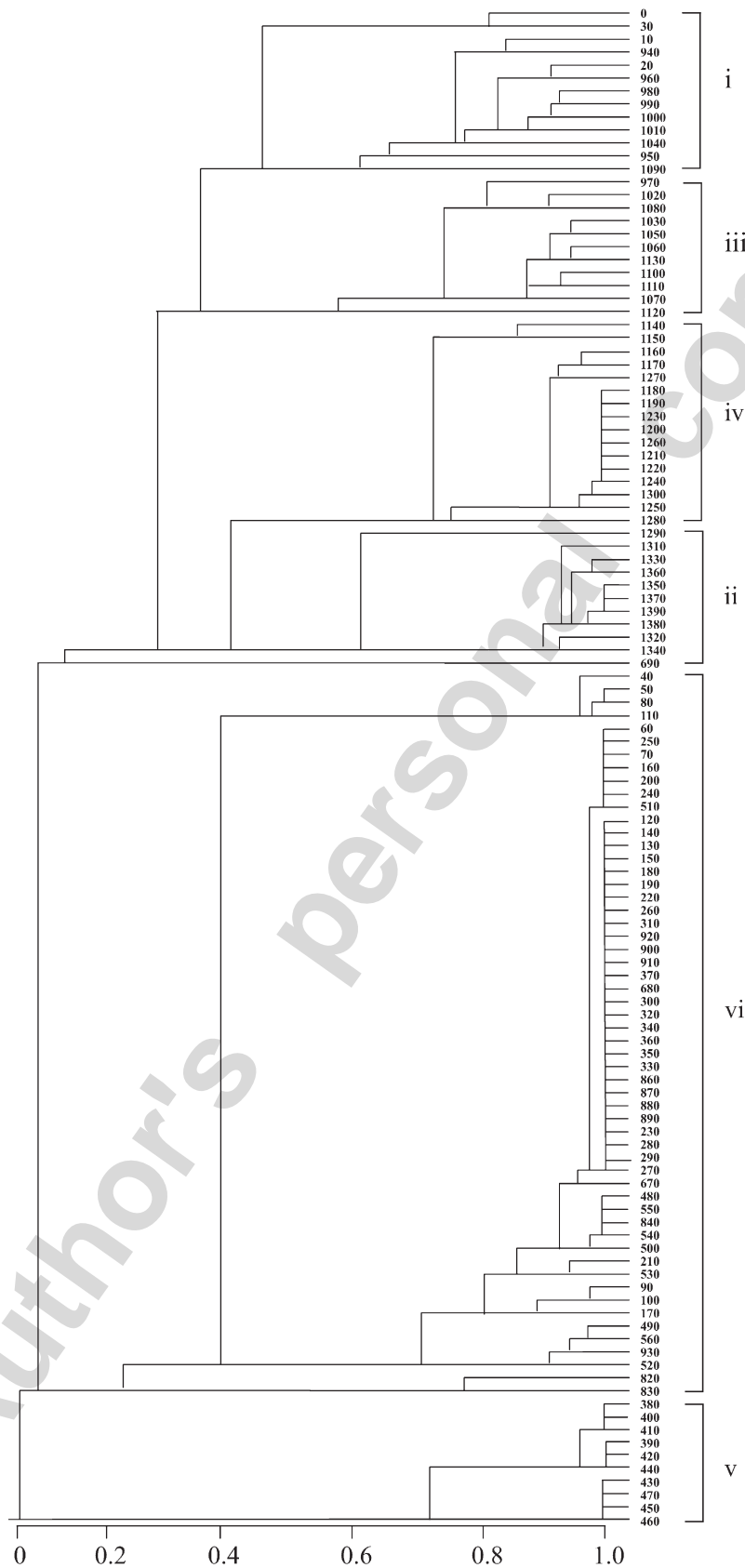


Fig. 7. Q-mode cluster analysis of ostracods from core MD-32. Each sample is designated by the depth (in centimetres) in the core. The numbers (i) to (vi) are ordered in relation to the depth which is represented by the biofacies, from open shallow marine (i) to lacustrine (vi). This is the same numbering system applied to Fig. 5. The x-axis indicates the degree of correlation between the branches of the cluster.

Table 3
Summary of the biofacies of core MD-32, determined by cluster analysis of ostracod assemblages

Biofacies	Ostracods	Samples	Environment
i	<i>Bairdiids</i> , <i>pectocytherids</i> , <i>Neocytheretta</i> , <i>Foveoleberis</i>	0–0.3, 9.4– 9.6, 9.8– 10.1, 10.4, 10.9	Open shallow marine
ii	<i>Cytherella</i> , <i>Cytherelloidea</i> , <i>Hemikritha</i> , <i>Phlytenophora</i>	12.9–13.9	Shallow marine
iii	<i>Xestoleberis</i> , <i>Cytheropteron</i> , <i>Praemunita</i>	9.7, 10.2, 10.3, 10.5– 10.8, 11.0– 11.3	Marginal marine
iv	<i>Loxococoncha</i> , <i>Venericythere</i> , <i>Parakrithella</i> , <i>Caudites</i>	11.4–13.9	Tidal channel
v	<i>Venericythere</i> , <i>Leptocythere</i>	3.8–4.7	Estuarine
vi _a	<i>Cyprideis</i> , <i>Ilyocypris</i>	0.6, 0.7, 0.9, 1.0, 1.2–3.7, 4.8–6.0, 6.7, 6.8, 8.2–9.3	Saline lacustrine
vi _b	<i>Limnocythere</i> , <i>Cyprinotus</i> , <i>Zonocyprretta</i>	0.4, 0.5, 0.8, 1.1	Fresh lacustrine
Barren	None	6.1–6.6, 6.9– 8.1, 14.0– 14.8	Exposed

McKenzie, 1989), 36% to Western Australia and Joseph Bonaparte Gulf (Hartmann, 1979; Howe and McKenzie, 1989; Clarke et al., 2001) and 13% to the east coast of Australia (Hartmann, 1981; Yassini and Jones, 1995). Links with Indonesian waters are strong, with approximately 43% of identified species reported including 29 from the Java Sea (Kingma, 1948; Dewi, 1997, 2000), 23 from the Sunda Shelf and Singapore platform (Mostafawi, 1992), 17 species from the Malacca Strait (Whatley and Zhao, 1987, 1988) and 17 from the southeast Malay Peninsula (Zhao and Whatley, 1989). Affinities also exist with fauna from the South China Sea, the north Indian Ocean and the southwestern Pacific (e.g. Zhao et al., 1985; Zhao and Wang, 1988; Ikeya and Cronin, 1993; Bonaduce et al., 1976, 1980; Benson, 1964; Hornibrook, 1952; Swanson, 1979). Although not identified to species level, five of the non-marine ostracods found in the core samples have also been recovered from freshwater sites from northwestern Australia (McKenzie, 1966). There is no modern analogue for freshwater ostracods from the region immediately surrounding the Gulf. Two species of the genus *Hemikritha*, characteristic of the tropical waters of the Java and South China Seas, have been identified for the first time outside of those immediate regions.

Commonly co-existing ostracod species have been assigned to assemblages throughout core MD-32 by cluster analysis (Fig. 6). In the following text the abundance of ostracods is described as dominant

(>20%), abundant (>10%), common (>5%), present (<5%, occurring in all samples of the assemblage), rare (present in only some samples), very rare (present in few samples), with respect to the relative standardised number of valves per gram of dry sediment. Species that are statistically insignificant, but indicative of the depositional environment, have been included and are labelled accordingly. All taxa mentioned are as adult forms; juveniles are noted where present.

3.2. Cluster analysis

Cluster analysis has been performed to compare the composition of ostracod assemblages (R-mode) and their distribution through the core material of MD-32 (Q-mode) using the program CORRMAT/PROG (Jones and Facer, 1981). A data matrix was constructed, comprising the number of valves per gram of dry sediment of each ostracod genus within each core sample examined. Adults and juveniles have not been differentiated. To simplify the matrix, the same restrictions with regards to genus abundance and representation as were defined for the taxa plot (Fig. 5) have been applied here. Similarly, samples barren of ostracods (i.e. samples in the depth ranges 6.0–6.6 m, 7.0–8.1 m and 14.0–14.8 m) have been eliminated from the analysis. In total, the matrix comprises 37 genera (or groupings) from 117 samples. A further restriction was imposed on the data set, whereby the value 0.01 was appointed for cases in which a genus was not identified in a sample, but was found in similar assemblages at other depths, and the value 0 was assigned for cases in which a genus was not identified in a sample and was not found in similar assemblages at other depths. This data-forcing was imposed to compensate for the large number of “zeros” in the data set. The analysis was performed by calculating the similarity matrix based on relative species abundance for each depth sample. The measurement of the similarities is determined using the cosine–theta similarity coefficient for the Q-mode analysis and a Pearson product moment correlation coefficient for the R-mode analysis.

R-mode cluster analysis groups those assemblages found to commonly co-exist within the depth samples. In this study, six faunal groups have been identified (Fig. 6), numbered corresponding to the biofacies (Fig. 5). Q-mode cluster analysis correlates core depth samples with similar faunal assemblages, with the inference that they were deposited under similar conditions. In this study, six broad groupings have been identified (Fig. 7). These may be correlated with the biofacies defined by the R-mode analysis. The results of the cluster analysis are summarised in Table 3.

4. Discussion

The assemblages of co-existing ostracods that occur throughout core MD-32 are distinct and correlate largely with units defined from variations in the sedimentology of the samples (Fig. 8). Facies subdivision is based on the cluster analysis, supplemented by the sedimentary characteristics (Reeves et al., accepted for publication). Ecological comparisons are made with common species identified in the gulf and surrounding region, as shown in Table 4. The distribution of ecological associations ascribed to each of the units and subunits determined for the core as defined by the ostracod species present is also depicted in Fig. 8. Much of the facies variation is dictated by the height of sea level, relative to the two oceanic boundaries to the gulf—the Arafura Sill (−53 m) and Torres Strait (−12 m). As such, the composite relative sea-level curve of Waelbroeck et al., 2002 (Fig. 9) is used in conjunction with a series of previously established dates (Chivas et al., 2001; Reeves et al., accepted for publication) to provide a chronology for the sequence. The Marine Isotope Stages (MIS) are used as a temporal reference for the sequence observed in the cores.

4.1. MIS 6/5

The basal unit (Unit 7) of core MD-32 (14.84–13.95 m), which has been dated at both the top and base to around 130 ka BP (Chivas et al., 2001), is barren of microfauna, the coarse fraction comprising abundant quartz and mica within a matrix of mottled iron-oxide-rich clays. The lack of ostracods indicates an environment of too high energy, exposed or under-saturated with respect to calcium carbonate either to support ostracods or preserve the valves. The unit is considered to have been deposited by episodic flooding within a restricted basin with exposed margins and subsequent pedogenesis, prior to the onset of the last interglacial.

4.2. MIS 5

The ostracod assemblages throughout Unit 6 (13.95–9.3 m) (Fig. 8) represent a fluctuating open to restricted marine environment, which may be correlated with the sea-level variations through MIS 5.

4.2.1. MIS 5.5

The first evidence of ostracods within the recovered core material occurs at a core depth of 13.9 m. The dominant species, *Cytherella semitalis*, is represented by at least five instars, including adults. This assemblage

(Biofacies (ii)), which is characteristic of open, shallow marine sea-grass environments, continues through Subunit 6f (13.9–13.1 m) and includes *C. semitalis*, *Cytherelloidea malaccaensis*, *Phlyctenophora zealandica* and *Hemikritha* spp. There are strong affinities with similar environments in Southeast Asia. The association resembles assemblages described from the Java Sea west of Bawean Island (Dewi, 1997), the Malacca Straits (Whatley and Zhao, 1987, 1988) and the Malay Peninsula (Zhao and Whatley, 1989).

Taxa common in modern, nearby shallow Pacific waters, such as *Neocytheretta* species are poorly represented and the pectocytherinids are absent. The number of both ostracodal and foraminiferal species broadens through the subunit, with the establishment of stable, shallow marine conditions. In addition, the presence of planktic foraminifers and pteropods indicates a greater influence of marine waters. It is likely that both the Arafura Sill and Torres Strait were breached at this time. This is consistent with deposition during MIS 5.5, when sea level locally reached +3 m compared with the present (Nott, 1996).

4.2.2. MIS 5.4

The Subunit 6e (13.0–11.7 m) is clearly noted by the shift in the ostracodal assemblage to the dominance of *Loxococoncha judithae*. From 12.6 m, this species is represented by at least five instars. Other prominent taxa of the assemblage comprise Biofacies (iv). *Loxococoncha* is commonly found in marginal marine and inner shelf waters and tidal channels with abundant algal matter and a sandy substrate. The sedimentological evidence supports an increase in energy of the environment, in part due to closer proximity to the coast, and increased fluvial activity. This assemblage suggests a decline in sea level or restriction of the marine conditions, which is consistent with MIS 5.4, during which levels dropped to around −45 m (Fig. 9).

The anomalous assemblage toward the base of this subunit at 12.9 m, includes poorly preserved valves of Biofacies (ii) ostracods, planktic foraminifera and no *L. judithae*, indicating reworking from laterally deposited sediment. This may have been caused by a brief channel connection, or wash-over from across the Arafura Sill.

Although the genus *Loxococoncha* is cosmopolitan, the species *L. judithae* has thus far only been described from northern Australian waters (Howe and McKenzie, 1989; Yassini et al., 1993). This is a prolific and opportunistic genus, showing a high degree of endemism at species level. Both *Parakrithella pseudornata* and *Venericythere papuensis* have been identified

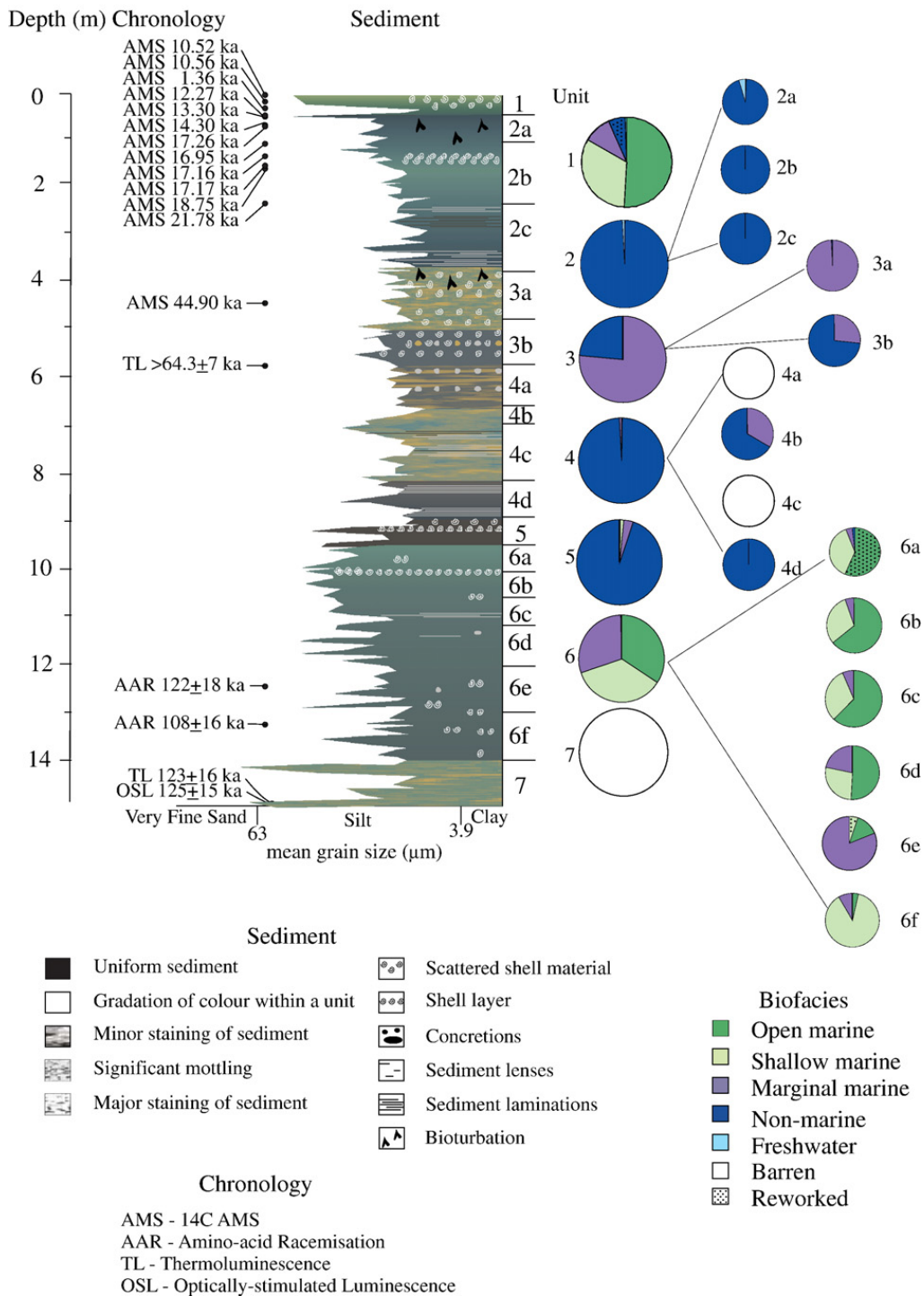


Fig. 8. Sedimentary log of core MD-32, showing the distribution of ecological associations ascribed to each of the units and subunits as defined by the ostracod species present. Note that the term marginal marine here includes also the estuarine and tidal channel biofacies. The ¹⁴C AMS dates shown are calibrated, where possible.

throughout Southeast Asian shallow marine waters (e.g. Whatley and Zhao, 1987, 1988; Zhao and Whatley, 1989; Mostafawi, 1992; Dewi, 1997).

4.2.3. MIS 5.3

A gradual change in the composition and the character of the samples occurs from the underlying unit and

through Subunit 6d (11.7–11.3 m) (Figs. 5, 8). The coarse sediment fraction is more abundant, largely due to an increased quantity of microfauna. Although *L. judithae* dominates to 11.5 m, the other species, including *Xestoleberis darwinensis*, *Pterygocythereis velivola* and *Neocytheretta* spp., suggest a more hospitable environment in a shallow marine setting. These

Table 4

Ecological ranges of all ostracod species found in core MD-32, inferred from modern surface samples and previously described distributions. Numbered localities correspond to those in Fig. 4. Thin lines indicate the taxon is present, thick lines represent abundant taxa

Species	Marine		Estuarine			Lacustrine		
	Open	Shallow	Marginal	Channel	Lagoon	Saline	Oligohaline	Fresh
<i>Eupolycope</i> sp.	—	—	—	—	—	—	—	—
<i>Polycope</i> <i>favus</i>	—	—	—	—	—	—	—	—
<i>Polycope</i> sp.	—	—	—	—	—	—	—	—
<i>Cytherella</i> <i>semitalis</i>	—	—	—	—	—	—	—	—
<i>Cytherella</i> cf. <i>hemipuncta</i>	—	—	—	—	—	—	—	—
<i>Cytherelloidea</i> <i>malaccaensis</i>	—	—	—	—	—	—	—	—
<i>Cytherelloidea</i> cf. <i>excavata</i>	—	—	—	—	—	—	—	—
<i>Cytherelloidea</i> sp.	—	—	—	—	—	—	—	—
<i>Paranesidea</i> <i>onslowensis</i>	—	—	—	—	—	—	—	—
<i>Neonesidea</i> <i>australis</i>	—	—	—	—	—	—	—	—
<i>Phlyctenophora</i> <i>zealandica</i>	—	—	—	—	—	—	—	—
<i>Phyletocythere</i> cf. <i>pellucida</i>	—	—	—	—	—	—	—	—
<i>Argilloecia</i> cf. <i>lunata</i>	—	—	—	—	—	—	—	—
<i>Pontocypris</i> cf. <i>attenuata</i>	—	—	—	—	—	—	—	—
<i>Pontocyprina</i> sp.	—	—	—	—	—	—	—	—
<i>Neocytheretta</i> <i>adunca</i>	—	—	—	—	—	—	—	—
<i>Neocytheretta</i> <i>spongiosa</i>	—	—	—	—	—	—	—	—
<i>Neocytheretta</i> <i>spinobifurcata</i>	—	—	—	—	—	—	—	—
<i>Alocopocythere</i> <i>goujoni</i>	—	—	—	—	—	—	—	—
<i>Neocytheretta</i> <i>vandijki</i>	—	—	—	—	—	—	—	—
<i>Neocytheretta</i> <i>cornea</i>	—	—	—	—	—	—	—	—
<i>Hemikritha</i> sp.	—	—	—	—	—	—	—	—
<i>Hemikritha</i> sp. 1	—	—	—	—	—	—	—	—
<i>Stigmatocythere</i> <i>indica</i>	—	—	—	—	—	—	—	—
<i>Venericythere</i> <i>papuensis</i>	—	—	—	—	—	—	—	—
<i>Venericythere</i> <i>darwini</i>	—	—	—	—	—	—	—	—
<i>Pistocythereis</i> <i>bradyi</i>	—	—	—	—	—	—	—	—
<i>Pistocythereis</i> <i>euplectella</i>	—	—	—	—	—	—	—	—
<i>Pistocythereis</i> <i>cribriformis</i>	—	—	—	—	—	—	—	—
<i>Pterygocythereis</i> <i>velivola</i>	—	—	—	—	—	—	—	—
<i>Bythocytheropteron</i> <i>alatum</i>	—	—	—	—	—	—	—	—
<i>Rhombocythere</i> <i>alata</i>	—	—	—	—	—	—	—	—
<i>Bythoceratina</i> <i>hastata</i>	—	—	—	—	—	—	—	—
<i>Bishopina</i> <i>spinulosa</i>	—	—	—	—	—	—	—	—
<i>Copytus</i> <i>posterosulcus</i>	—	—	—	—	—	—	—	—
<i>Parakrithella</i> <i>pseudornata</i>	—	—	—	—	—	—	—	—
<i>Pseudopsammocythere</i> cf. <i>reniformis</i>	—	—	—	—	—	—	—	—
<i>Cytheropteron</i> <i>wrighti</i>	—	—	—	—	—	—	—	—
<i>Semicytherura</i> sp.	—	—	—	—	—	—	—	—
<i>Caudites</i> cf. <i>javana</i>	—	—	—	—	—	—	—	—
<i>Caudites</i> <i>exmouthensis</i>	—	—	—	—	—	—	—	—
<i>Microcytherura</i> cf. <i>punctatella</i>	—	—	—	—	—	—	—	—
<i>Leptocythere</i> <i>hartmanni</i>	—	—	—	—	—	—	—	—
<i>Leptocythere</i> <i>lacustris</i>	—	—	—	—	—	—	—	—
<i>Callistocythere</i> <i>warnei</i>	—	—	—	—	—	—	—	—
<i>Mediocytherideis</i> (<i>Sylvestra</i>) <i>jellineki</i>	—	—	—	—	—	—	—	—
<i>M. (S.) jellineki</i> <i>carpentariensis</i>	—	—	—	—	—	—	—	—
<i>Loxococoncha</i> <i>judithae</i>	—	—	—	—	—	—	—	—
<i>Cytherois</i> sp.	—	—	—	—	—	—	—	—
<i>Paracytherois</i> sp.	—	—	—	—	—	—	—	—
<i>Paracytheroma</i> <i>mangrovicola</i>	—	—	—	—	—	—	—	—
<i>Javanella</i> <i>kendengensis</i>	—	—	—	—	—	—	—	—
<i>Labutisella</i> <i>quadrata</i>	—	—	—	—	—	—	—	—
<i>Labutisella</i> <i>darwinensis</i>	—	—	—	—	—	—	—	—
<i>Praemunita</i> <i>broomensis</i>	—	—	—	—	—	—	—	—
<i>Praemunita</i> <i>capeyorkiana</i>	—	—	—	—	—	—	—	—

(continued on next page)

Table 4 (continued)

Species	Marine		Estuarine			Lacustrine		
	Open	Shallow	Marginal	Channel	Lagoon	Saline	Oligohaline	Fresh
<i>Praemunita</i> sp.	—————							
<i>Keijia nordaustriale</i>	—————							
<i>Keijia australis</i>	—————							
<i>Neomonoceratina bataviana</i>	—————							
<i>Neomonoceratina porocostata</i>	—————							
<i>Paijenborchella solitaria</i>	—————							
<i>Xestoleberis darwinensis</i>	—————							
<i>Foveoleberis cypraeoides</i>	—————							
<i>Limnocythere</i> sp.							—————	
<i>Cyprideis australiensis</i>			—————	—————	—————	—————	—————	
<i>Ilyocypris australiensis</i>				—————		—————	—————	
<i>Cyprinotus</i> cf. <i>cingalensis</i>				—————		—————	—————	
<i>Candonocypris</i> cf. <i>novaezealandiae</i>								—————
<i>Cypretta</i> sp.								—————
<i>Zonocyprretta</i> sp.								—————
<i>Darwinula</i> sp.								—————

species are common to the waters around northern Australia, having been described from the nearshore of the modern Gulf of Carpentaria (Yassini et al., 1993), Darwin Harbour (Howe and McKenzie, 1989) and the Joseph Bonaparte Gulf (Clarke et al., 2001). The

higher degree of preservation, along with a decrease in quartz content and an increase in the amount of pyrite in the samples, particularly infilling carapaces, support a lower energy environment, more distal from fluvial influence.

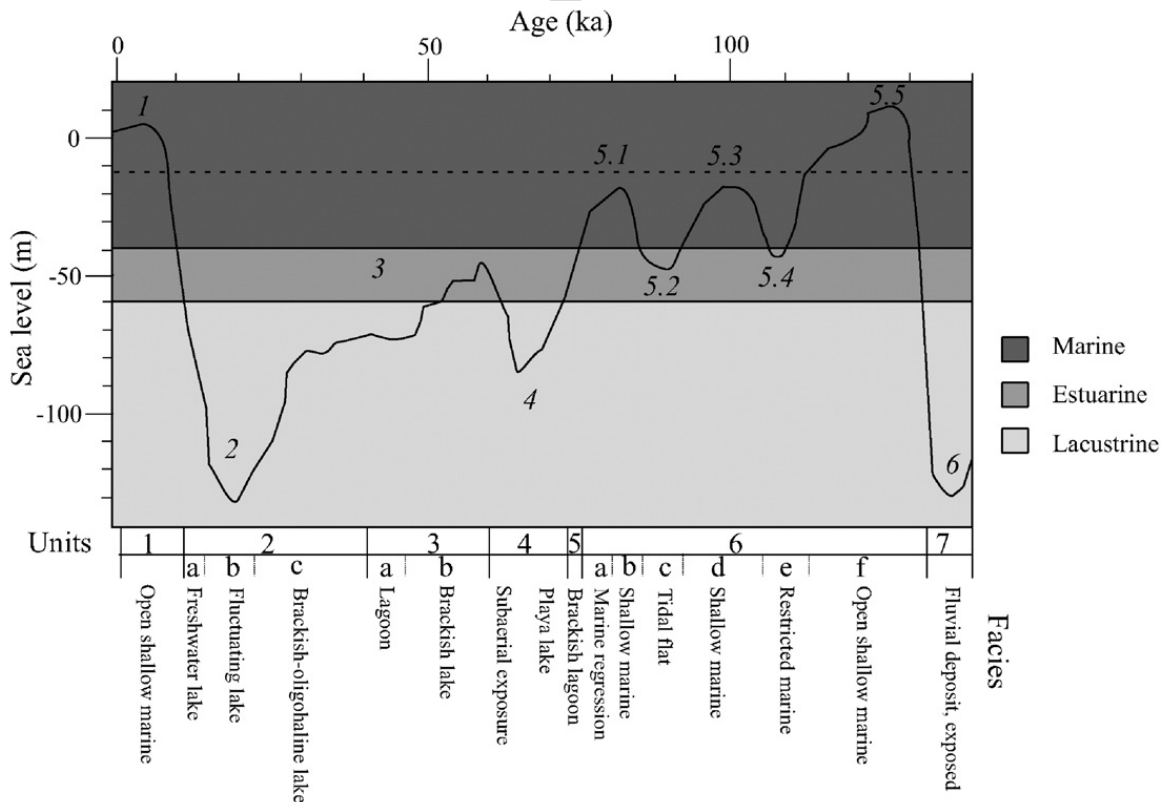


Fig. 9. Relative sea-level through the last glacial cycle (labelled on the curve with the Marine Isotope Stages (MIS) 1 to 6) as determined by Waelbroeck et al. (2002), showing an approximation of the height of the Arafura Sill (solid horizontal lines either side of - 50 m) and Torres Strait (dashed horizontal line at - 12 m) and likely environments in the gulf region. The sedimentary and ecological facies of core MD-32 are shown in the lower abscissa.

The introduction of bairdiids to the assemblage from 11.4 m indicates a stronger marine influence. By 11.3 m, the taxa are well established, with both *Paranesidea onslowensis* and *Neonesidea australis* represented by numerous instars. As bairdiids require full marine conditions to reproduce, a deepening of water is evident. Both *N. australis* and *P. onslowensis* have been recorded in the modern Gulf of Carpentaria, the latter only in a sample taken from nearest the Arafura Sill (Yassini et al., 1993). Whereas *P. onslowensis* has only been described from northwestern Australia (Hartmann, 1978; Howe and McKenzie, 1989), *N. australis* is known also from the east coast (Yassini and Jones, 1995).

The abundance and diversity of the assemblage, dominated by *Xestoleberis darwinensis*, suggests a productive, phytal, open shallow marine environment. Based on ostracodal evidence, it is also possible that Torres Strait was breached by this stage, or at least sea level was well above the Arafura Sill height. The planktic foraminifers and pteropods that were present in Subunit 6f have not been identified from these samples, suggesting that sea level was not restored to its former highstand, consistent with the levels of MIS 5.3, around –20 m (Fig. 9).

4.2.4. MIS 5.2

A restriction of marine conditions and higher energy environment is noted in the samples from Subunit 6c (11.2 m to 10.7 m) (Figs. 5, 8). Although the assemblage is diverse, the abundance of ostracods is reduced. The fauna represents a progression of the underlying subunit, dominated by Biofacies (iii). Most of these species are endemic to Australia. It is noteworthy that *Paranesidea* is absent from these samples, suggesting that this environment may be restricted or influenced by meteoric waters and hence unsuitable for this taxon, although *Neonesidea* persists. The low percentage of adult valves and the abundance of dwarfed and frosted tests of the foraminifer *Ammonia* spp.¹, suggest inhospitable or altered conditions. The numerous pyrite-filled valves and algal borings found on some of the *N. australis* valves indicate a low-energy environment with abundant organic matter and dissolution. The precipitation and preservation of gypseous laminae within the sediment further indicate a restricted and low-energy, evaporitic environment. The inter-layering

of gypsum with predominantly silty-clay sediment suggests periodic flooding by marine waters in a restricted lagoonal environment, with subsequent stagnation and drying. During MIS 5.2, sea level dropped to around –50 m, and remained low for longer than during MIS 5.4 (Lambeck and Chappell, 2001).

4.2.5. MIS 5.1

The enhanced diversity, abundance and preservation of ostracods throughout Subunit 6b (10.6–10.2 m) (Figs. 5, 8) are evidence of more amenable conditions. The basic assemblage remains the same as that of the underlying subunit, however the presence of taxa such as *P. onslowensis*, *Cytherella semitalis*, *Pterygocythereis velivola* and *Foveoleberis cypraeoides* indicate a return to a more open, shallow marine environment. The occurrence of several instars of the bairdiids, and the observation of hairs preserved on the valves of *N. australis* support these taxa being *in situ*. The fauna contains both local and cosmopolitan elements. Taxa such as *Labutisella quadrata*, *L. darwinensis* and *Callistocythere warnei* are endemic to tropical Australia, having been described from the Great Barrier Reef in the east, to the Kimberley in the west (Labutis, 1977; Howe and McKenzie, 1989; Yassini et al., 1993; Clarke et al., 2001). Other species, including *Neocytheretta adunca*, *Parakrithella pseudornata*, *Cytherelloidea malaccaensis* and *Pistocythereis* spp., are better known from the shallow seas of Southeast Asia (Whatley and Zhao, 1987, 1988; Zhao and Whatley, 1989; Mostafawi, 1992; Dewi, 1997).

Subunit 6a (10.1–9.3 m) is differentiated on the basis of the dominant ostracod taxa and the degree of diversity and preservation of the microfauna present. Species such as *P. onslowensis*, *Neocytheretta* spp. and *Praemunita* spp., which are present in the underlying assemblage, are dominant in these samples implying more open marine conditions. Conversely, shallow and marginal marine fauna is less abundant. Such an assemblage is found in the samples at the top of the core, Unit 1 (0.3–0 m) and in the sample described from nearest the Arafura Sill in the modern gulf (Yassini et al., 1993). Both *P. onslowensis* and *N. australis* exhibit three instars, indicating transportation. Deposition of Subunits 6a and 6b during the MIS 5.1 highstand of around –20 m and the subsequent regression is inferred (Fig. 9).

A shell-hash layer, indicating a shoreline feature, marks the start of Subunit 6a. Compared with the underlying subunit, the samples show poor diversity and degree of preservation. Although the taxa present are characteristic of the middle- or inner-shelf environment,

¹ The generic term *Ammonia* spp. is used here to represent all rotaliids in the form of *Ammonia*, including *A. beccarii*, *A. tepida* and *Helenina andersoni*. The differentiation between these species is currently being examined from the Carpentaria material and will be presented elsewhere.

both bleached and reworked valves are common, suggesting a recession of marine waters. In addition, foraminiferal diversity is reduced, with only robust taxa present, supporting this being a regressive phase. Those tests present are white and frosty in appearance indicating transportation and/or recrystallisation.

4.2.6. MIS 5/4

Unit 5 (9.3–8.95 m) is clearly delineated from the previous facies based on the dominance of two ostracod species, *C. australiensis* and *Leptocythere hartmanni* (R) of Biofacies (vi_a) and the foraminifer *Ammonia* spp. All of these taxa are known to have a marine ancestry, although adapted to marginal and restricted, even lacustrine waters of Na–Cl solute composition (Cann and De Deckker, 1981; Anadón, 1992). The first sample, at 9.3 m, comprises mostly juvenile *C. australiensis* and valves of other species, including *Callistocythere warnei*, *Praemunita broomensis* and *Cytherois* sp., all of which may occur in marginal, estuarine environments. At this time, marine waters must have been cut-off from the main body of the Gulf of Carpentaria, leaving a stranded waterbody of essentially marine composition.

A life assemblage of *C. australiensis* is present throughout the rest of the unit, best described as a ‘bloom’. Although the presence of *C. australiensis* is indicative of estuarine or non-marine waters, it is a euryhaline species, so gives little indication of the salinity of the water body. Isolated valves of *Ilyocypris australiensis* and *Darwinula* sp. have been transported from proximal oligohaline water. The valves of *L. hartmanni* (B) are heavily calcified through this unit, meaning that the water must have been supersaturated with respect to calcite. However, the small size, light weight and elongate and irregular sieve pores of the *Cyprideis* valves, indicate a carbonate-limited environment. Higher temperature may have prompted more rapid calcification, producing the crude reticulation of *L. hartmanni* (B). Other boundary conditions include the salinity and oxygen content of the water, either of which may have an effect on the life habits of the ostracods and calcification of the carapace.

The large amount of broken shell material in the unit, especially at 9.0 m, represents a shoreline facies, indicating the extent of the lake at the time. Small bivalves, gastropods and fish fragments are common. The shells are blackened and their shiny appearance due to pyritisation suggests a high amount of organic matter in a reducing, anoxic environment after the death of the organisms. Although a congeneric species, *C. torosa*, is known to withstand low-oxygen conditions (Aladin, 1993; Jahn et al., 1996; Gamenick et al., 1996), it is more than likely here that anoxia in the sediment occurred

after the death of the ostracods. The environment is evocative of a swamp or brackish lagoon, cut-off from marine influence, coincident with the drop in sea level below the sill around the MIS 5/4 transition.

4.3. MIS 4

The ostracod assemblages through Unit 4 are very poor with few of the ostracod species represented, and many of the samples are barren of microfauna. Much of the environmental interpretation of these samples has been extrapolated from the sedimentology (Reeves et al., accepted for publication). Deposition is associated with the sea-level lowstand of MIS 4. Subunit 4d (8.9–8.1 m) is characterised by fine-grained sediment and prismatic gypseous laminae; evidence of a low-energy non-marine environment with episodic flooding and subsequent evaporation. The rare ostracods that are found are predominantly juvenile *C. australiensis* valves with signs of abrasion. Reworking to this depositional environment is likely. Both *L. hartmanni* (B) and *Neomonoceratina bataviana* are common taxa in tidal channels. The poor preservation of the rare valves of these two species found in these samples also indicates transportation. The foraminifer *Ammonia* spp. are common to saline, non-marine settings with permanent water (Cann and De Deckker, 1981). The sugary and dwarfed tests found in these samples suggest a stressful environment, such as high temperature or lack of food, and probable *post mortem* recrystallisation. The abundance of pyrite favours reducing conditions, whereas gypsum indicates oxidising conditions, hence alternation of Eh conditions is suggested. Throughout the deposition of this subunit, the facies is likened to a low-energy, organic-rich playa-like closed basin with periodic flooding and evaporation. Sedimentation rates are higher than in the underlying unit.

Subunit 4c (8.0–7.0 m) is segregated on the basis of iron-oxide mottling of the sediment, caused by subaerial exposure and fluctuations in groundwater levels. The depositional environment is essentially the same as the underlying subunit, however post-depositional exposure indicates drier conditions. Pyrite is common in the samples, generally having been partially oxidised. Most of the samples are barren of ostracods, implying either an even less hospitable environment, dry most of the time or with strongly fluctuating salinity, or dissolution of valves during pedogenesis. Those valves that are present are juvenile, sugary and poorly preserved, again suggesting transportation and/or recrystallisation. Foraminifers, including *Ammonia* spp. and planktic species, are more common in these samples, representing a mixed

assemblage. Transportation, of the planktic species in particular, is indicated, as the tests show minor abrasion and their light weight and spherical shape allows them to be carried in suspension over long distances. This phenomenon was noted in the Alligator River, north Australia by Wang (1990) and Wang and Chappell (2001). A continuation of the underlying facies, though more remote from permanent water is interpreted.

The more diverse and abundant taxa of Subunit 4b (6.9–6.7 m) are a result of permanent water and more stable conditions in the environment at the time of deposition. An incursion of waters from the eastern Indian Ocean is evident in the lowermost samples with the presence of the shallow marine fauna *Cytherella semitalis* and *Hemikritha* sp., which are common to Subunit 6f. Channel connection across the Arafura Sill, rather than an open marine connection is postulated, coincident with MIS 4/3 transition around 60 ka BP (Waelbroeck et al., 2002; Chappell, 2002). The assemblage at 6.8 m is diminished, suggesting a regression of marine waters, with only marginal marine taxa remaining. The heavy primary calcification of *L. hartmanni* (B) implies a high concentration of calcium carbonate within the host water. By 6.7 m, the sample is dominated by *C. australiensis*, exhibiting several instars and accompanied by *L. hartmanni* (B) and charophyte oogonia fragments, revealing the establishment of a permanent non-marine waterbody. The presence of *Neomonoceratina bataviana* and *C. semitalis* valves however does suggest some continued tidal channel influence.

The samples from 6.6 m to 6.0 m are considered to be a Subunit (4a) of Unit 4 based on their diminutive fauna, indicating inhospitable conditions for ostracod habitation. The few ostracod valves that have been found are poorly preserved and all show evidence of reworking or dissolution. The fauna is common to non-marine or marginal settings. The presence of *I. australiensis* at 6.7 m indicates proximity to very low salinity water, as this is an essentially oligohaline species. The foraminiferal assemblage from 6.3 m to 6.1 m is better represented, with reworked tests of robust rotaliids, indicating transportation. *Ammonia* spp. is abundant and present in a variety of sizes, suggesting an *in situ* population. This foraminifer is able to withstand a wide range of salinities and moderately energetic waters. Samples of this subunit have an abundant coarse-fraction component, dominated by quartz and carbonate concretions. This is considered to have been deposited in a high-energy environment, most probably alluvial, with subsequent subaerial exposure and pedogenesis. The dissolution of the ostracod valves and *Ammonia* spp. is most likely due to post-depositional penetration of meteoric waters

through the sediment during increased fluvial periods, with subsequent precipitation of carbonate concretions. Flooding of waters across the Arafura Sill, silting up the inflow channels, resulted in a closed lake basin in the depocentre of the gulf region.

4.3.1. MIS 4/3

The vast abundance of *C. australiensis* with all instars present in the samples of Subunit 3b (6–4.8 m) indicates the presence of a permanent waterbody, restricted from marine waters. The dominance of *C. australiensis* in saline waters of Na–Cl solute composition, suggests that the waterbody derives from a marine origin. The small size of the adult valves may also be indicative of a stressed environment, such as high temperature or unusual water composition. A life assemblage of this species is present, although the adults in the first few samples show evidence of dissolution. This may be a seasonal phenomenon, with minor etching of the adult valves caused, *post mortem*, by meteoric water.

Saline conditions, becoming fresher above 5.3 m, are suggested by the sieve pore morphology of *C. australiensis* (Fig. 10). The heavily calcified valves of *L. hartmanni* (B) in the lower samples, and the dominance of *L. hartmanni* (R) in the higher samples, also indicate more saline conditions, freshening up through the subunit. The shell-layer at 5.0 m, with abundant bivalved molluscs and gastropods, is most likely a lake shoreline feature. The chalky nature of the shells is evidence of later exposure. A brackish waterbody, with later restriction and minor pedogenesis, with permeation of meteoric water is postulated. This is coincident with MIS 3, around 55 ka BP.

4.4. MIS 3

Subunit 3a (4.7–3.8 m) is differentiated from 3b on the basis of the dominant taxa, Biofacies (v). *Venericythere darwini* is abundant and well preserved, with all instars present in most samples, indicating a life assemblage. Adults are absent from the base of the subunit, but the presence of poorly preserved *C. australiensis* valves suggests that these valves may have been transported. *V. darwini* is a marginal marine species, common to intertidal settings in southeast Asia. Its presence is evidence of a renewed contact with marine waters in a low energy environment, such as an open lagoon or estuary. Small and heavily calcified valves of *L. hartmanni* (B) suggest a restrictive environment. Whole carapaces of both *V. darwini* and *L. hartmanni* (B) are common, indicating rapid burial. The species *L. hartmanni* (R) occurs in the upper samples of the subunit, but as dwarfed and coarsely reticulated valves.

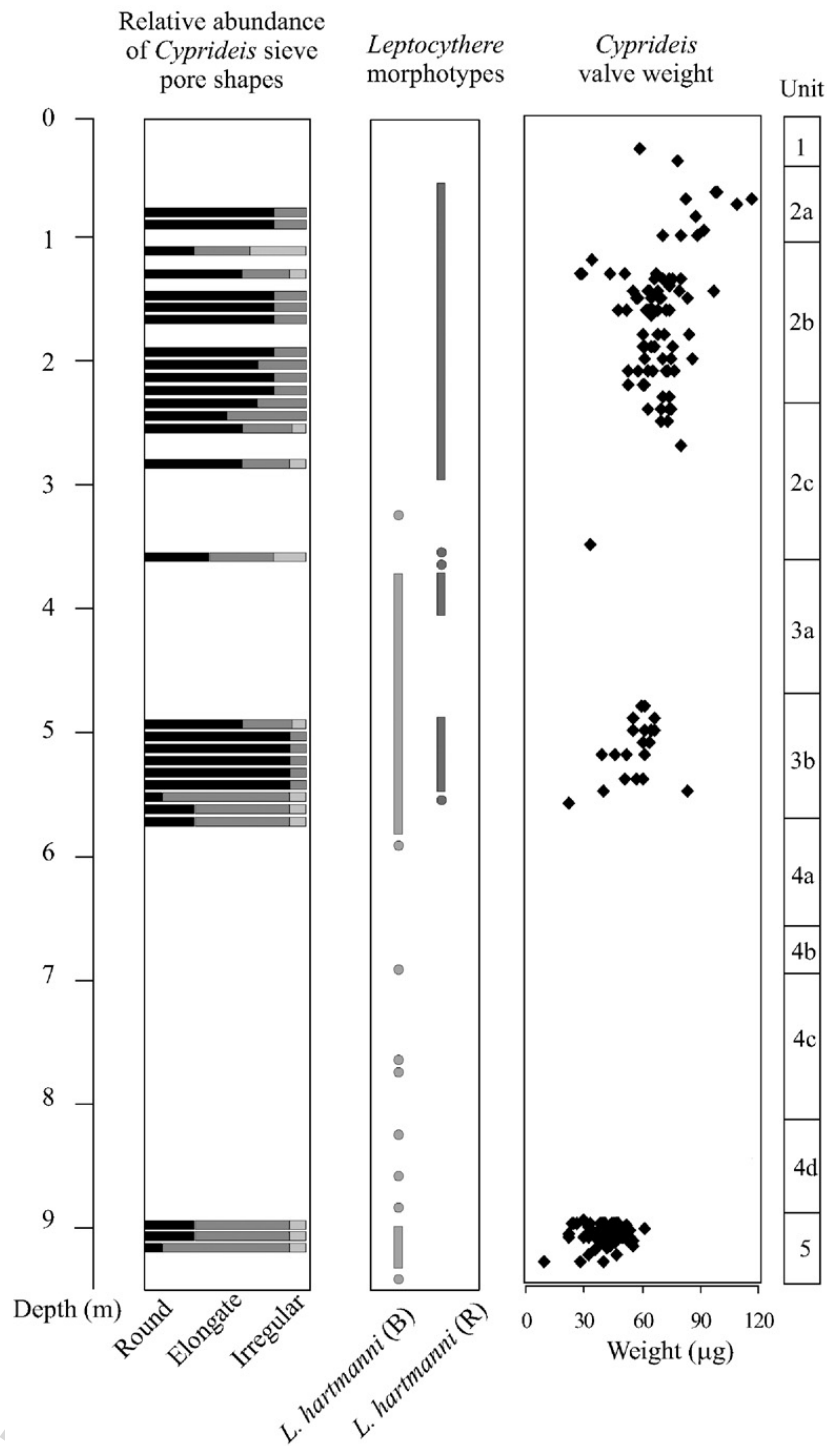


Fig. 10. Graphs displaying the morphological variation of the ostracod taxa *Cyprideis australiensis* and *Leptocythere hartmanni* in the upper 9 m of core MD-32.

This may represent the upper salinity tolerance limit for this taxon. The presence of other species, namely *Neomonoceratina bataviana* and *Phlyctenophora zealandica*, in the upper samples indicates tidal channel influence in this restricted environment toward the top of the unit. The sea-level curve of Waelbroeck et al. (2002) shows a decreasing sea level throughout MIS 3, however records

from the Huon Peninsula indicate slightly higher levels of ~ 50 m at around 52 ka BP, (Chappell et al., 1996; Lambeck and Chappell, 2001; Chappell, 2002). This is consistent with the ostracod facies shift. This unit was previously identified as the basal unit V of longest cores collected by Torgersen et al. (1985), representing marine material. Whilst an influence of marine waters is apparent,

a true marine environment is not supported by the sequence in core MD-32, presented here.

4.4.1. Lake Carpentaria

The reestablishment of lacustrine conditions is evident through Unit 2. This is synonymous with unit II of Torgersen et al. (1985, 1988). The recession of marine waters to below the sill height is inferred. This transition has been dated in the other cores from the present campaign to around 40 ka BP (Reeves et al., accepted for publication). Units IV and III of Torgersen et al., (1985, 1988), represented by a shell-hash layer and thin, authigenic calcite laminae, are not present in this core, but have been identified from core MD-33, extracted from the deepest part of the modern gulf (Reeves et al., accepted for publication). The maintenance of a lake implies increased inflow from the surrounding rivers to the basin, and outflow channels across the sill.

C. australiensis resumes dominance in the assemblage through Subunit 2c (3.7–2.8 m) (Biofacies (vi_a)), indicating permanent water. As with Subunit 3b, mostly juvenile valves are represented in the lower samples. Adults, where present, show evidence of dissolution, which may indicate increased seasonality. The dominance of irregular sieve pores and small valve size suggests saline conditions. Whole carapaces infilled with pyrite are common, caused by rapid burial followed by anoxia within the sediment.

The introduction of *Ilyocypris australiensis* as a significant component of the assemblage indicates fresher conditions than those seen lower in the core. The absence of many juvenile instars and any whole carapaces of *I. australiensis* indicates a transported assemblage. As the species is known to inhabit streams and temporary pools, transportation of juvenile valves via winnowing in wetter seasons is likely. *C. australiensis* and *I. australiensis* have not been found to coexist in the modern environment. Hence it is suggested that either the environment fluctuated between saline and oligohaline over short time periods, such as seasonally, or that *I. australiensis* was transported by stream inflow to the lake. This is supported by stable isotope analysis of valves of *C. australiensis* and *I. australiensis*, which indicate a different origin for the two species (Reeves, 2004.). The sample at 3.3 m, with both *L. hartmanni* (B) and *V. darwini* valves suggests a brief reconnection to marginal marine water, or reworking of marginal sediments.

4.5. MIS 2

Continued lacustrine conditions are evident through Subunit 2b (2.7–1.2 m). The increase in the abundance of

ostracods and the life assemblage of *C. australiensis* with well-calcified valves suggest stable conditions and a deeper, more extensive lake at this time. The dominance of rounded sieve pores in the *Cyprideis* valves of these samples indicates lower salinity conditions and carbonate ion saturation. This is supported by the abundance of other taxa, such as *L. hartmanni* (R) and *I. australiensis*. Again, the lack of juvenile *I. australiensis* valves and the evidence of minor recalcification in the vestibulum of some of the adult valves indicate either partial dissolution of the assemblage or transportation of this species from temporary pools to a more established waterbody. The degree of reticulation in the valves of *L. hartmanni* (R), from heavily to finely reticulated up through the subunit (Fig. 10), may be caused by a decrease in the solute concentration of the waterbody, due to increased freshwater inflow. A deeper lake and possibly cooler conditions, with less evaporation are postulated.

The presence, although in low abundance, of the ostracods *Zonocyprretta* sp. and *Candonocypris* cf. *no-vaezelandiae* of Biofacies (vi_b) in Subunit 2b imply fresh water. As *C. australiensis* is not characteristic of, but can survive in freshwater environments, it is suggested that these isolated valves of other taxa were transported to the core site in the lake, perhaps from an adjacent fresh pool. Only adults and fractured valves have been identified. The presence of the 'rogue' marine ostracods, *Rhombocythere alatum* and *Pterygocythereis velivola* at 2.5 m and 1.7 m respectively, which have been identified from tidal channels of the modern gulf (Yassini et al., 1993), may be derived from sediment around the lake margins. The presence of reworked rotaliid foraminifers in the samples from 2.2 m to 1.7 m supports this. This may be an indication of a minor contraction of the lake around the time of the last glacial maximum. There is no evidence of desiccation of the lake basin during this time, supporting the interpretations of the trace element analyses of ostracods (De Deckker et al., 1988).

The abundance of shell material in the assemblage from 1.5 to 1.1 m, including freshwater bivalves, planospiral molluscs, fish fragments and charophytes also indicates an increase in the energy of the environment, such as a shoreline feature, and freshwater conditions. This shell-rich unit has been found in each of the cores and has similar radiocarbon dates throughout, of around 19.0–17.2 cal ka BP (Reeves et al., accepted for publication). An increase in meteoric water input and transportation of material is inferred. This is contemporaneous with an increase of monsoon activity following a rapid rise in sea level, in the Bonaparte Gulf of the Sunda Shelf, detailed by Yokoyama et al. (2000, 2001).

A change in the character of the samples occurs in Subunit 2a (1.1–0.4 m). The two species, *C. australiensis* and *I. australiensis* alternately dominate the assemblage. Periodic fluctuation is suggested, which may be indicative of increased seasonality. At this stage, the sampling resolution does not allow definition of the periodicity concerned. The diversity and increased abundance of freshwater taxa; including finely reticulate *L. hartmanni* (R), *Limnocythere* sp., *Cypretta* sp. and *Cyprinotus* sp. and charophyte gyrogonites, indicate this to be the freshest environment recovered in the core material. An increase in alkalinity is also implied. In the transfer function of salinity for non-marine ostracods of southeast Australia, Radke et al. (2003) found these genera to be associated with low salinity, bicarbonate-rich waters. This grouping of taxa has also been described from the Na⁺–Mg²⁺–Cl[–]–HCO₃[–] rich, monsoon deposited waters of the Kimberley in northwestern Australia (Williams and Buckney, 1976; McKenzie, 1966). De Deckker et al. (1988) also note a freshening of waters in the uppermost lacustrine sediments. An active outflow channel across the sill and an increased input from meteoric water sources, i.e. greater precipitation, is inferred. This unit has been radiocarbon-dated from the other cores collected during this campaign to around 14–12 cal. ka BP (Chivas et al., 2001).

Other ostracod species, such as *Microcytherura* cf. *punctaella* and the presence of rare planktic foraminiferal tests, indicate the influence of estuarine waters, with the rising sea level beyond the Arafura Sill. This fauna may have been transported some distance in suspension before being deposited in the lake. A decrease in the overall abundance of ostracods may be due to more variable lake conditions, or may indicate deeper water in this region of the lake at the time of deposition.

4.6. MIS 1

The incursion of marine waters into the lake is apparent in core MD-32 from 0.38 m upward, dated to around 10.8 cal. ka BP. This was previously identified as unit I by Torgersen et al. (1985, 1988), and dated to around 10 ka BP (uncalibrated), however improved techniques give a more precise dating of this event. The samples of the uppermost unit contain a large amount of broken shell material, indicating dynamic conditions. The fauna is diverse and open shallow marine in affinity, with such taxa as bairdiids and the necktic ostracod *Polycope* spp. Neither planktic foraminifera nor pteropods were recovered. Planktic foraminifera are very rare in the modern Gulf of Carpentaria, due to the shallow nature of the basin. Many of the ostracod taxa,

such as *Cytherella semitalis*, *Hemikrithe* sp. and *P. onslowensis* have a Southeast Asian affiliation, while *Labutisella* spp. and *Praemunita* spp., which are common to the Pacific Ocean, have not been recovered from these samples.

This assemblage resembles that of Subunit 6a (10.1–9.4 m); the last identifiably marine unit before sea level dropped below the Arafura Sill. This suggests that the most recent breaching of Torres Strait is not clearly represented in core MD-32. The assemblage is clearly mixed; in addition to the marine fauna, valves of *C. australiensis* and *I. australiensis* have been identified, reworked from the underlying unit. This phenomenon has been documented by De Deckker et al. (1988) in cores retrieved from the deepest section of the modern gulf, and in surface samples by Yassini et al. (1993) and represents relict material.

5. Conclusions

From the observation of ostracod assemblages preserved in core sediment from the Gulf of Carpentaria, clearly defined facies may be delineated, and verified by cluster analysis of the assemblages present and comparison with modern analogues from the region. Large sections of the core are dominated by the environmentally tolerant species *C. australiensis* and *L. hartmanni*. Both species show a range of morphological variation, in sieve pore shape and valve weight in the former and surface reticulation in the latter. Observations of these changes through the core provide information on variations in hydrologic conditions at the time of valve formation, such as salinity and solute composition. In addition, post-depositional effects of sorting, recrystallisation and preservation provide information on the energy and conditions of the environment of deposition.

The combined analysis of faunal assemblages, morphological variation and preservation reveals five main phases of deposition in the Gulf of Carpentaria region through the last glacial cycle, which are closely correlated with the global sea-level curve:

- 1) marine, fluctuating between open shallow marine, similar to today, partially enclosed and restricted lagoonal waters, through MIS 5;
- 2) brackish to hypersaline playa, with episodes of subaerial exposure, through MIS 4;
- 3) pluvial conditions, with a return of restricted marine waters to the basin through MIS 3;
- 4) lacustrine phase, varying from saline to freshwater, through 40–12 ka BP, with the freshest lake phase around 17.5–14 ka BP;

5) marine transgression from around 10.8 ka BP to present.

This study extends the knowledge of the palaeoenvironment of the gulf region beyond the most recent lake phase and through the last full glacial cycle. In addition, further dating and more detailed sampling and analysis of the biofacies allow a more comprehensive understanding of the former Lake Carpentaria. Whereas the level of the sea relative to the two boundaries (the Arafura Sill and Torres Strait) of the present gulf is the major driving factor determining aquatic conditions and the biota within the basin, climatic conditions, particularly the activity of the Australian monsoon, are shown to have a more localised affect on the hydrology and hydrochemistry of the host water.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at [doi:10.1016/j.palaeo.2006.09.012](https://doi.org/10.1016/j.palaeo.2006.09.012).

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